Permittivity of Highly Absorbing Oxide Ceramics in Millimeter Waves

Mohammed N. Afsar[a], King Wang[b], Peter Liu[b], and Konstantin A. Korolev[a, c]
[a]Department of Electrical and Computer Engineering, Tufts University, Medford, MA 02155 USA
[b]AGILTRON Incorporated, Woburn, MA 01801 USA
[c]Extremely High Frequency Medical and Technical Association, Moscow 125009, Russian Federation

***Abstract*—Complex dielectric permittivity of highly absorbing oxide ceramics have been studied in a broadband millimeter wave frequency range for the first time. Transmittance and reflectance measurements have been performed using a free space quasi-optical spectrometer, equipped with a set of high power backward wave oscillators, tunable in *Q*-, *V*- and *W*-frequency bands. Ceramic materials have found to be almost non-transparent (opaque) in millimeter waves with extremely high values of permittivity. Frequency dependences of dielectric permittivity, calculated from precision transmittance and reflectance spectra are presented.**

I. Introduction and Background

MODERN millimeter wave and terahertz industry heavily relies on solid oxide and ferrite ceramics which have found their extensive uses as absorbers and/or reflectors [1]-[3]. A free space quasi-optical spectroscopy technique has been successfully employed to study absorbing ferrite ceramics in millimeter waves [4], [5]. This approach enables authors to obtain precise transmission and reflection spectra to determine the dielectric properties of both isotropic and anisotropic ceramics in the millimeter wave frequency range from a single set of direct measurements. This paper examines for the first time the complex permittivity of oxide ceramics in the millimeter wave frequency range from 30 to 120 GHz.

II. Experimental Results

Oxide ceramic materials [$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$] were developed at AGILTRON Inc., Woburn, MA. The material fabrication started with the preparation of ceramic powder from a chemical coprecipitation technique, followed by ceramic firing using a hot-press system. The material was cut into a disc shape, and double-side polished. Planar, disc-shaped ceramic samples were 1.43 mm thick and 21 mm in diameter. Precise surface parallelism of ceramic samples has been achieved to ensure the accuracy of the measurement.

Dielectric measurements have been performed by the free space quasi-optical spectrometer in both transmittance and reflectance mode. High vacuum, high power backward wave oscillators have been applied as sources of coherent radiation continuously tunable in the millimeter wave range from 30 to 120 GHz. A couple of horn antennas and a set of polyethylene lenses along the propagation path from the source antenna to the receiver antenna have been adjusted to form a Gaussian beam and to focus it into the sample. Details of free space millimeter wave quasi-optical spectroscopy and measurement uncertainties have been addressed earlier [4], [6].

Two consecutive frequency sweeps with and without the sample in the quasi-optical path have been made and transmittance and reflectance spectra have been recorded. After obtaining the transmittance and reflectance spectra of the oxide ceramic materials, optimization procedures were applied to extract the best-fit dielectric of the measured samples. Transmittance and reflectance spectra of oxide ceramic materials are shown below in Fig. 1.

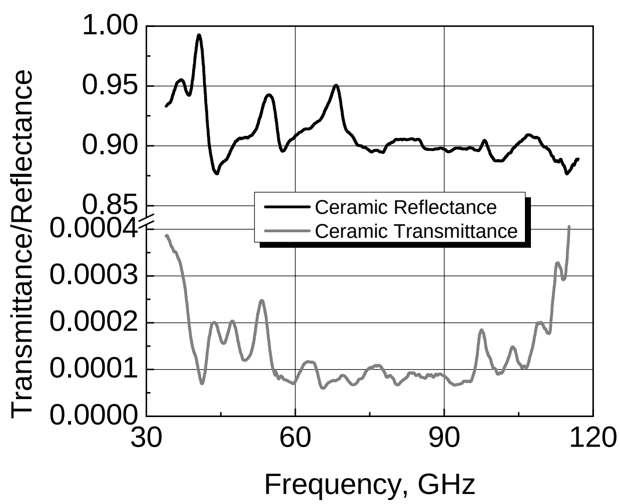

Fig. 1. Transmittance and reflectance spectra of oxide ceramic sample in millimeter waves. The thickness of the sample is 1.43 mm.

The transmittance and reflectance can be expressed with well known equations [7] given below.

$$T = E\frac{(1-R)^2 + 4R\sin^2\psi}{(1-RE)^2 + 4RE\sin^2(\alpha+\psi)} \qquad R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

$$\varphi = \alpha + \arctan\frac{ER\sin^2(\alpha+\psi)}{1-ER\cos^2(\alpha+\psi)} + \arctan\frac{k}{n^2+k^2+n} - \arctan\frac{k}{n+1}$$

$$E = \exp\left(-\frac{4\pi kdf}{c}\right) \qquad \alpha = \frac{2\pi ndf}{c}$$

$$n + ik = \sqrt{\varepsilon\mu^*} \quad (1) \qquad \psi = \arctan\frac{2k}{n^2+k^2-1}$$

Here, c is the speed of light, d is the thickness of the sample, n, k, μ, and ε represent the refractive index, absorption index, magnetic permeability and dielectric permittivity of the sample respectively. T, R and φ represent the transmittance,

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reflectance and phase of the transmitted electromagnetic wave, respectively.

It has been found that oxide ceramic material under study turns out to be almost opaque substance in the millimeter wave frequency range. Almost all millimeter wave radiation reflects from the surface of the sample. Recorded value of the reflected radiation is found to be more than 90%. The level of transmitted signal through the ceramics has been observed to be around 0.01% which is extremely low. A contradiction that the sum of transmitted and reflected signal is not equal to 1 can be attributed to the diffraction of the radiation on the edges of the sample, the random errors in the transmittance/reflectance measurements originating from the thermal instability of the generator, the dynamic range or signal to noise ratio and standing waves problem [4], [7]–[9].

The reflection of the radiation from the elements of the quasi-optical channel and an inserted specimen form the distinctive pattern in the transmittance/reflectance spectra. The employment of film and carbon loaded foam absorbers along the quasi-optical path helps to reduce essentially the standing wave pattern but does not completely eliminate it. The distribution of the standing waves is changed when a specimen is introduced into the measurement channel. The standing waves repeatedly appear in the transmittance spectrum as high frequency noise. These standing waves do not yield any ambiguity in the results; as they occur with high frequency and their average level give the true value of the transmittance.

Due to high enough accuracy of the measurements and recording technique, as well as smooth and slow frequency scan to ensure the thermal stability of the source, the periodic structures for both transmittance and reflectance spectral signals have been clearly resolved. Real and imaginary parts of dielectric permittivity of oxide ceramics have been calculated from transmittance and reflectance spectra and presented below in Fig. 2.

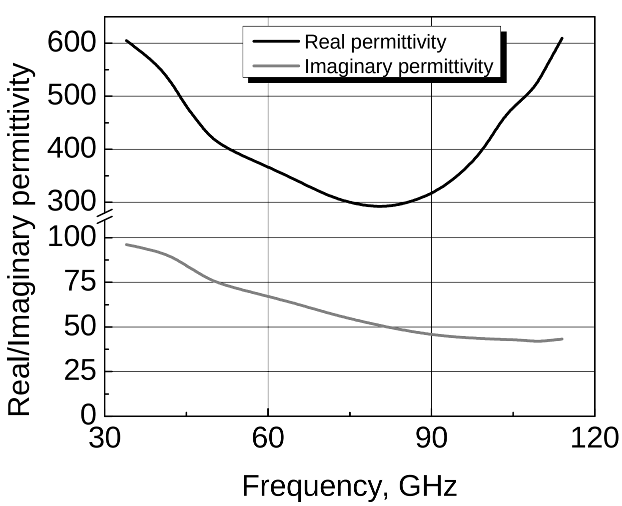

Fig. 2. Real and imaginary parts of dielectric permittivity of oxide ceramic sample.

Extremely high values of dielectric permittivity of oxide ceramics through the whole millimeter wave frequency range have been found. Decreasing of the imaginary part of dielectric permittivity towards higher frequencies has been observed. Quite unusual behavior in the frequency dependence of the real part of permittivity has been found. Real permittivity shows a clear minimum at the middle of the millimeter wave range around 80 GHz. On the other hand, in both transmittance and reflectance spectra no relatively deep minima/maxima have been observed. The origin of that unusual phenomenon is not clear for the authors yet. More detailed investigations, including precise monitoring on the sample preparation process and purity control are expected to be performed in the future.

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REFERENCES

[1] J. Smit and H. P. J. Wijn, *Ferrites*. Eindhoven, the Netherlands: Philips Technical Library, 1961.

[2] Y. W. Buchner, R. Schliebs, G. Winter, K. H. Buchel, Industrial Inorganic Chemistry, V. C. H. Weinheim, 1989.

[3] T. Sakai, Y. Chen, C. N. Chinnasamy, C. Vittoria, and V. G. Harris, “Textured Sc-doped barium-ferrite compacts for microwave applications below 20 GHz”, *IEEE Trans. Magn*., vol. 42, pp. 3553-3555, Oct. 2006.

[4] M. N. Afsar, I. I. Tkachov, and K. N. Kocharyan, “A novel *W*-band spectrometer for dielectric measurements,” *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 2637-2643, Dec. 2000.

[5] K. A. Korolev, S. Chen, and M. N. Afsar, “Complex magnetic permeability and dielectric permittivity of ferrites in millimeter waves”, *IEEE Trans. Magn*., vol. 44, pp. 435-437, Apr. 2008.

[6] K. N. Kocharyan, M. N. Afsar, and I. I. Tkachov, “Millimeter-wave magnetooptics: New method for characterization of ferrites in the millimeter-wave range,” *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2636-2643, Dec. 1999.

[7] A. A. Volkov, Yu. G. Goncharov, G. V. Kozlov, S. P. Lebedev and A. M. Prokhorov, “Dielectric measurements in submillimeter wavelength region”, *Infrared Phys*., vol. 25, pp. 369-373, 1985.

[8] A. A. Volkov, G. V. Kozlov, S. P. Lebedev, Optimization of dielectric parameters measurements of substances in a submillimeter region”, *Radiotechnika I Electronika*, vol. 24, No. 7, pp.1405-1412, 1979.

[9] K. A. Korolev, S. Chen, and M. N. Afsar, “Millimeter-wave transmittance measurements on ferrites near ferromagnetic resonance”, *IEEE Trans Instrum. Meas*., vol. 57, pp. 1388-1393, July 2008.